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Reprint of “Computational study of the particle size effect on a jet erosion wear device”☆

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ABSTRACT

Computational fluid dynamics (CFD) is a useful tool to predict the erosion behaviour over geometries exposed to conditions of severe erosion wear. This work shows how CFD can be used to virtually characterize the wear behaviour of materials used in several hydraulic components, including turbomachinery systems, in which it is important to consider the effect of particle size. In addition, this work develops a methodology for determination and validation of the constants involved in the well-known Tabakoff-Grant model for erosion prediction using the erosion wear obtained via erosion testing in a jet tribometer reported in the literature as a reference. From the experimental data, an optimization algorithm was performed to determine the optimal values of Tabakoff-Grant model constants for ASTM A743 grade CA6NM martensitic stainless steel. The simulated erosion rate agrees with the experimental data for the material analysed in jet erosion simulations with impact angles ranging from 15° to 90°. The change of the angle of maximum erosion rate for small particles, which has been reported in the literature via experimentation, was explained satisfactorily. The results showed that the erosion rate with smaller particles is affected by fluid flow, since small particles tend to follow the flow streamlines, while larger particles move according to the conditions imposed by the jet at its outlet. The effective impingement angle against the surface for small particles is lower than the impingement angle for large particles; therefore, the angle of maximum erosion rate, measured between the jet and the sample's surface, for small particles increases.

1. Introduction

Erosive wear due to sand particles is one of the most important problems that must be taken into account at the design stage for hydraulic turbines, particularly for run-of-the-river facilities. Wear conditions are influenced by the river's water conditions and local hydrological conditions during the operation period. This is the case for several plants located at Los Andes and the Himalayas that, have been affected by erosive wear via sand particles [1–5] with severe damage to the machines’ components, causing premature loss of efficiency and increasing corrective maintenance and subsequent economic losses.

During the past decades, computational fluid dynamics (CFD) has become an important tool to design hydraulic machinery under several operational conditions, including sand wear erosion. One of the well-known models for erosion behaviour in ductile materials due to hard particles is the Tabakoff-Grant model [6]. However, literature regarding the erosion model's constants that define the interaction between different hard particles and materials is limited. To obtain this information, it is necessary, but not sufficient, to perform experimental tests in which variables such as concentration, particle velocity, impingement angle, particle size and particle shape can be related to the material's erosion rate. Next, this information must be processed and the constants of the model obtained for implementation within the CFD software.

In general, erosion caused by hard particles exhibits a different behaviour in ductile and brittle materials. In the case of ductile materials, the ductility of the surface allows the absorption of the particle energy when it impinges the surface at near normal angles; however, when the particle hits the surface with lower angles, the surface tends to lose material by cutting. According to Hutchings [7], in ductile materials, the angles that exhibit major losses of material are in a range of 15–30°, while in brittle materials, the angle for maximum

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mass loss is 90°.

Experimental results obtained by Romo et al. [8] include a comparison of the slurry erosion resistance of a Stellite 6 coating and 13Cr-4Ni stainless steel. They performed tests of slurry erosion at several impact angles defined between the sample and the jet, obtaining the characteristic curves for erosion interactions between sand and the tested materials. Using a particle size of 300 µm, they observed a behaviour in accordance with the general statement explained previously, with an angle for maximum erosion of approximately 45° for both materials. Shivamurthy et al. [9] evaluated the resistance to slurry erosion of Stellite 6 relative to the base material 13Cr-4Ni stainless steel at particle sizes of 100 µm and 375 µm and several impact angles between the sample and the jet. Their analysis showed that for largest particles, the 13Cr-4Ni Stainless steel exhibits a similar behaviour as that found by Romo, while the Stellite 6 coating undergoes maximum erosion rate at an angle of 60°. For the smallest particles, the Stellite 6 coating maximum erosion angle is 90°, while in the 13Cr-4Ni steel, it is 60°; however, they do not provide an explanation of the cause of the change in this angle with the particle size. In addition, in their analysis about wear mechanisms, they found that for both materials, i.e., Stellite 6 coating and 13Cr-4Ni steel, there is evidence of micro cutting, plastic deformation with chip fracture, crater lips and plowing marks in all tested angles; generally, these mechanisms are associated with ductile behaviour.

Although 13Cr-4Ni stainless steel is currently the most common material used in the manufacturing of hydraulic turbines and although experimental data regarding erosion are available, the coefficients of the erosion models have been neither obtained nor used in CFD simulations of these machines. Eltvik et al. [10] used CFD to investigate erosion problems in a Francis turbine constructed from 13Cr-4Ni steel using the Finnie and the Tabakoff-Grant erosion models with AISI 304 stainless steel constants. They found that the Tabakoff-Grant model provides more reliable erosion predictions than Finnie's model since it uses five constants that relate the erosion to the particles and the surface properties; in contrast, Finnie's model employs only two constants. The obtained results were qualitatively verified by inspecting a worn Francis turbine at Cahua power plant in Peru.

Others authors, such as Mansouri et al. [11] combined CFD results with experimental data obtained from a normal impinging jet test submerged in water using slurry with sand particles on AISI 316 stainless steel specimens to develop an equation that allows for erosion prediction. They used CFD simulations with low Stokes number (in this condition the particles tend to follow the streamlines of the fluid) to characterize the particle impact velocity, impingement angle on the surface, which is affected by the fluid flow, and frequency at specific locations on the specimen. The obtained data were correlated with the measured erosion depth of the specimen subjected to the impingement jet tests to obtain the correlation.

In this work, CFD analysis is performed to predict erosion by hard particles of CA6NM stainless steel, which is equivalent to 13Cr-4Ni stainless steel. To achieve this goal, experimental results reported in the literature were used to determine the coefficients for the Tabakoff-Grant erosion model [6]. The methodology used in determining the coefficients is explained with the aim of helping with the model's use for other materials using experimental data. The coefficients are validated and used to perform a computational study of the particle size effect of the erosion behaviour of CA6NM stainless steel.

2. Materials and methods

2.1. Erosion model

The effect of particles on the wear of a ductile material surface is modelled via CFD coupled with the erosion model developed by Tabakoff and Grant [6,12]. The model consists of a solid dispersed phase (particles) immersed, transported and diffused in a continuous incompressible fluid (water) phase, and evolved in a Lagrangian way. Simulations can be performed using either one-way or two-way coupling. In one-way coupling, the effect of the particles on the fluid is ignored. In two-way coupling, the effect of particles on the fluid is modelled with momentum source terms in the Navier Stokes equations [13]. The dimensionless erosion rate E is determined from the Tabakoff-Grant model:

$$E = k_1 f(\gamma) V_p^2 \cos^2\gamma [1 - R_T^2] + f(V_{PN}) \tag{1}$$

$$f(\gamma) = \left[1 + k_2 k_{12} \sin\left(\gamma \frac{\pi/2}{\gamma_0}\right)\right]^2 \tag{2}$$

$$R_T = 1 - k_4 V_p \sin\gamma \tag{3}$$

$$f(V_{PN}) = k_3 (V_p \sin\gamma)^4 \tag{4}$$

$$k_2 \begin{cases} 1.0 \ if \ \ \gamma \le 2\gamma_0 \\ 0.0 \ if \ \ \gamma > 2\gamma_0 \end{cases} \tag{5}$$

where the dimensionless variable E corresponds to the ratio of the mass loss due to erosion to the particle's mass, V_p is the impact velocity of the particle, γ is the angle of impact, γ_0 is the angle of maximum erosion, R_T is the tangential restitution ratio and k_1, k_{12}, k_3, and k_4, are constants that depend on the particle properties (e.g., hardness, shape) and the surface material. The constants define the reference speeds V_1, V_2, and V_3 implemented in the CFD software:

$$V_1 = \frac{1}{\sqrt{k_1}} \quad V_2 = \frac{1}{\sqrt[4]{k_3}} \quad V_3 = \frac{1}{k_4} \tag{6}$$

The constants are obtained through an adjustment of the experimental data (Section 3.1). The erosion rate of an arbitrary surface is calculated as follows:

$$E_r = E^* \dot{N}^* m_p \tag{7}$$

where E_r is the erosion rate due to a particle, m_p is the average of one particle mass, and $\dot{N}$ is the particle number rate, which is a representative value of the particle concentration in the medium [13]. The shape factor is an indication of the roundness of the particle: a particle with a shape factor value of 1.0 is spherical, while a particle with a shape factor of 0.1 is an irregular particle with sharp edges, which generally causes more damage to a surface than a spherical particle. In the CFX solver, the shape factor is related to the drag forces on the particle, while the effect of this factor on the surface wear is related to the experimental constants of Tabakoff-Grant model. The data are normalized with the goal of transforming the numerical and experimental values to a suitable scale for comparison with the erosion model. The transformed values are defined as follows:

$$N_E = \frac{E_r}{V_j A_o \rho_{H_2O} (\frac{C}{1-C})} \tag{8}$$

where N_E is the dimensionless normalized erosion, E_r is the erosion rate in kg/s, V_j is the average jet velocity in m/s, A_o is the cross-sectional area of the jet's outlet, C is the sand concentration or mass fraction and ρ_{H_2O} is the water density in kg/m^3.

2.2. CFD configuration

The fluid domain for this study, which was adapted from [8], corresponds to a jet erosion bench and is shown in Fig. 1. Six impingement angles were simulated (15°, 30°, 45°, 60°, 75° and 90°).

The model was discretized using a structured mesh (Fig. 2), and refined near the zone of the specimen surface affected by hard particle erosion.

To reach a numerically independent result, convergence analysis of both the mesh size and the number of representative particles was